Creating the Wood Supply of the Future

Barry Gardiner and John Moore

Abstract Global demand for wood as a raw material is growing with a projected annual increase in industrial roundwood consumption of between 1.3 % and 1.8 % up to 2030. This rise is driven by the projected growth in the world's population and economic activity. Much of the increased consumption will be in the rapidly expanding economies of China, India and south-east Asia and the escalating use of wood for biomass, particularly in Europe. The potential to expand forestry will be limited in the region of highest growth (Asia and the Pacific rim, with the exception of China) because of competing land-uses and high population densities. In addition there is an ever increasing requirement for forests to provide a range of environmental services such as helping to provide clean air and water, protecting existing biodiversity and this has led to an ever expanding area of protected forests across the globe.

The result of these pressures on forestry is that there will be ever more reliance on managed forests, particularly planted forests, in order to satisfy this increasing demand for wood. While much of the product demand will remain as at present there will be an additional need for more wood in rapidly expanding sectors such as biomass and engineered wood products. This means that forests need to produce more wood per unit area and these wood products need to be more carefully designed to meet the increasing expectations of end users around product performance. This is partly driven by the performance levels of competing materials. Although this sounds daunting the methods and tools are available to make this a reality, but it will require forestry and the forest/wood chain to respond by adopting technologies and techniques that modernise the production and allocation of wood products along the whole production chain from forest to final end use.

B. Gardiner (✉)
Forest Research, Northern Research Station, Roslin, Midlothian, Scotland, UK

INRA-Unité EPHYSE, 33140 VillenaveD'Ornon, France
e-mail: barry.gardiner@bordeaux.inra.fr

J. Moore
Scion, Private Bag 3020, 3046 Rotorua, New Zealand
e-mail: john.moore@scionresearch.com

T. Fenning (ed.), *Challenges and Opportunities for the World's Forests in the 21st Century*, Forestry Sciences 81, DOI 10.1007/978-94-007-7076-8_30,

Expanding wood production in line with predicted global demand is entirely possible with the use of genetically improved material and management focussed on production and reducing losses from biotic and abiotic agents. The challenge is to do this in a manner that allows production to remain "sustainable" for the foreseeable future. At the same time the technology exists to make much more focussed use of the material from the forest with allocation decisions taking place as early as possible in the wood chain. In addition information on physical properties will be "tagged" to the material so that informed decisions can be made at every stage along the processing chain. The technologies available include aerial and satellite remote sensing (in particular with LiDAR), ground based scanning, acoustic technology, x-ray scanning, NMR scanning and Fourier Transform Infrared spectroscopy (FTIR). In this chapter we discuss how by combining improved productivity and improved allocation within the wood chain through the use of modern information systems it will be possible to meet the wood supply demands of the twenty-first century. The forest will become an integrated part of the wood chain with the volume and properties of the material well characterised and available at every stage of the journey from the forest to the final product.

1 Introduction/Background

In 2008 global wood usage was around 4.6 billion cubic meters. Of this around 40 % was used for wood fuel and 33 % as roundwood. The market in wood-based products has increased from $60 billion to $257 billion in the 20 years up to 2008 (FAO 2009a), mainly in wood panels and secondary processed wood products (SPWP). All the evidence suggests that global wood consumption will continue to increase (Fig. 1) despite the recent short-term reduction in demand due to the global financial crisis. Predictions suggest a trade of $450 billion by 2020 of which 40 % will be in SPWP. At the same time FAO (2010a) report that between 2000 and 2010 there was a net loss of forested area of 5.2 million hectares per annum from a global forest area of 4 billion hectares. This was mainly due to a large loss in primary forest (13 million ha/year), which has been partly compensated for by large scale commercial planting. The current area of planted forests is approximately 264 million hectares and is increasing by approximately 5 million hectares per annum.

Currently, 30 % of the world's forests are primarily used for wood and non-wood products (FAO 2010a). In the future the majority of wood will come from managed planted forests (plantations)[1] and dependence on natural forests will decline. This switch to planted forests is due to the fact that this appears to be the only way

[1] New forests are usually established through the planting of seedlings or the sowing of seeds. Subsequent regeneration of the forest may either be in the same way or through natural regeneration if the conditions are suitable. In the highly productive forests that have been recently established in many parts of the world, planting of seedlings is the primary method of establishment and regeneration, in part because this method can be used to introduce genetically improved material. However, natural regeneration is the traditional method of regeneration in the older managed forests that historically have provided a large proportion of the world's wood supply, such as Central Europe and North America, Fennoscandia, the Baltic States and Russia.

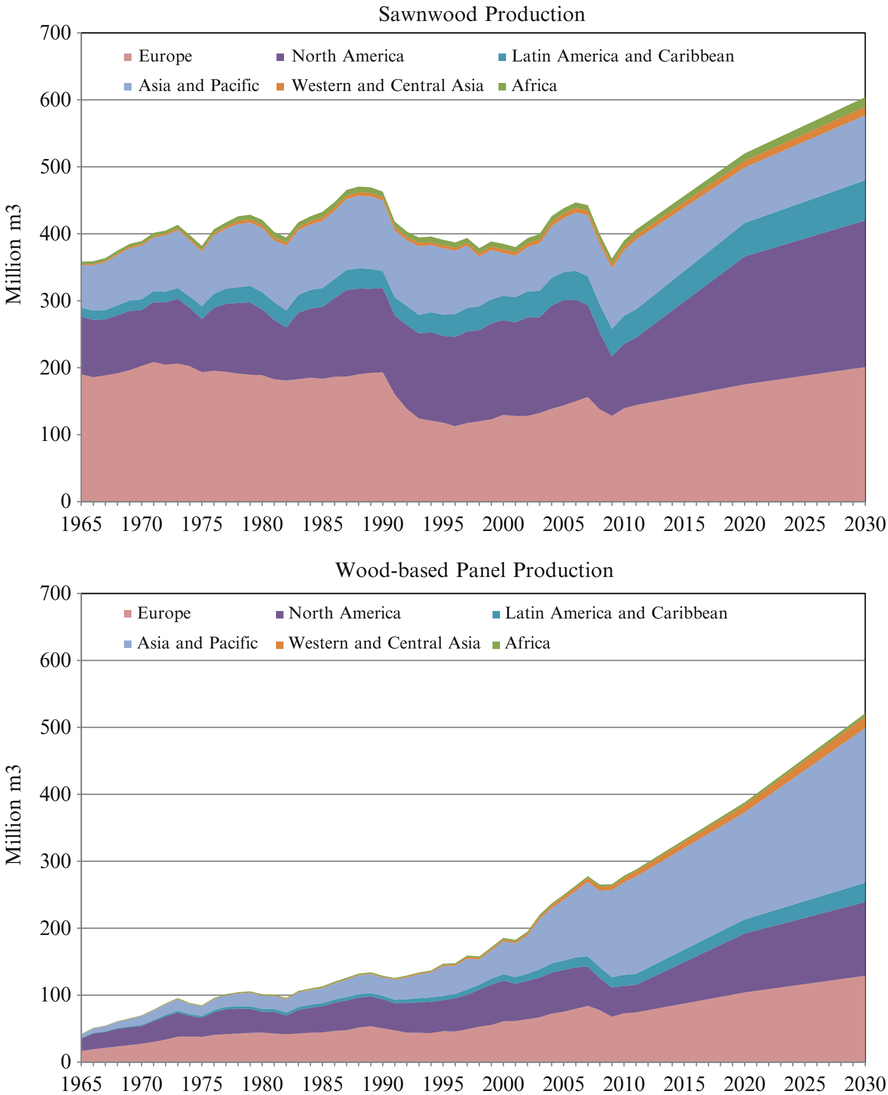

Fig. 1 Past and projected consumption of sawn wood and wood-based panels (reproduced from data in Jonsson and Whiteman 2008; FAO 2009a)

enough wood can be provided to meet the world's future requirements (Fenning and Gershenzonand 2002; Fenning et al. 2008). It is also partly due to mounting pressure to protect natural forests, which are increasingly valued for the ecosystem services they provide (e.g. biodiversity, and soil and water conservation) rather than for their provisioning services (FAO 2009a), even though some people argue that it is possible to maintain productivity from natural forests without deleterious effects (e.g. Putz et al. 2008). Already 50 % of the entire world's wood fibre comes

from planted eucalyptus forests and it is forecast that the total area of planted forests will reach almost 450 million hectares by 2020 with 255 million hectares in the tropics (FAO 2007). In addition the protective and social role of forestry is increasing but it is difficult to quantify exactly what impact this will have on forest productivity. Ownership is also changing with a shift from public ownership, which is currently at 80 %, to communities, individuals and private companies (FAO 2009a).

In principle, the additional area of planted forests could meet global wood demand assuming no change in bioenergy consumption (Fig. 2). Currently, woody biomass provides 50 EJ (~10 % of world energy needs), which it makes it the fourth most important source of energy after coal, oil and natural gas. It is estimated that biomass could provide 270 EJ (Ladanai and Vinterbäck 2009). Annual global primary wood production is equivalent to 4,500 EJ for comparison.

Altogether this suggests that forestry is going to have major challenges to continue to meet the world's demands for wood for both those areas that have traditionally dominated (e.g. solid timber, pulp and paper, and panel products) and emerging end-uses (e.g. biomass, biomaterials and chemicals). An increasing percentage of this supply will come from planted forests, the majority of which will be in the tropics. The major issues are how to provide this wood material at competitive prices in a sustainable manner. Since an increasing level of material must come from planted forests the management of these forests and the utilisation of the material from them will have increasing focus.

2 Increasing Wood Production

There is a clear need for increased wood production, increased use of recycled wood and more efficient use of the wood that is produced. Sedjo (1999) sets out the possibilities for increasing the worldwide production of wood. He argued that planted forests offer the possibility of providing much of the world's wood needs while at the same time protecting natural forests. He identified 11 major regions that had actual or potential promise for industrial planted forests: Pacific Northwest, US south, Brazil (Amazonia), Southern Brazil, Chile, Australia, New Zealand, South Africa, Gambia-Senegal, Nordic-Sweden, Finland, Borneo and Indonesia. All of these except Gambia-Senegal have emerged as important areas containing planted forests and in addition there have been significant developments in the Iberian Peninsula and Uruguay. Planted forests are now actively being developed in China, Japan, Korea and Indonesia (Table 1). Most of these new forests are on former agricultural land.

Sedjo (1999) believed that planted forests will increase in importance and the major impediment is the need for long term investment. The trend at the moment seems to be for internal local investment rather than external overseas investment in those countries most rapidly developing their planted forests. A second impediment is environmental concerns and planted forests needs to show that they can offset the need to harvest natural forests and increase the provision of ecosystem services, such as enhanced biodiversity, improved water quality and erosion control, to degraded ex-agricultural land.

Fig. 2 Current and projected areas of planted forest and wood production from planted forests (Carle and Holmgren 2008)

Table 1 Planted forest area by country (From Sedjo 2010)

Country	Forest plantation (1,000 ha)
China	45,083
India	32,578
Russia	17,340
United States	16,238
Japan	10.682
Indonesia	9,871
Brazil	4,982
Thailand	4,920
Ukraine	4,425
Iran	2,284

If bioenergy consumption continues to rise as predicted, then the increasing area of planted forests may not provide on their own enough wood raw-material to meet world demand (see Ince et al. 2011) for an assessment of the impact on the US forest sector of an expansion in wood energy consumption). In addition the increasing need to protect natural forests puts additional pressure on planted forests. Therefore, in the same manner as agricultural production (FAO 2012) there is likely to be a squeeze between raw material demand and the land resource available to provide this raw material and the pressure is likely to be most intense in the poorer countries of the world (Tilman et al. 2011).

When there is an increasing pressure on resources there appear to be a number of philosophies that people take regarding the issue (Pretty 1997):

1. Business as Usual Optimism: The market will provide based on biotechnology, increasing productive area and a slowing down of demand as the world's population begins to stabilise.
2. Environmental Pessimism: The ecological limits to growth have already been reached and we will be unable to sustainably supply the increasing and changing demand.
3. Industrialised World to the Rescue: The developing world cannot manage and the modernised processes of the industrialised world will provide what is needed and help protect the natural environment in the developing world. This suggests that production will move to the industrialised world leaving the developing world with forest reserves.
4. New Modernism: There will be intensification in the use of existing land with much more focus on a "science-based" approach. The system will be more sustainable because it will be focussed on a smaller area.
5. Sustainable Intensification: Integrated use of a range of methods and technologies to manage pests, nutrients, soil and water. Degraded or marginal lands will be reintroduced into production. There will be increasing emphasis on using natural processes to substitute for external inputs (e.g. fertilisers).

The first philosophy appeared to be correct until recent developments when it became clear that this is not a sustainable solution in the long term and can only work when there is an essentially unlimited supply of raw material. The second philosophy may be correct on this occasion but it has consistently underestimated the ability of society to deal with resource demands over many decades. The third philosophy is no longer relevant with the huge industrial developments taking place in countries like Brazil and Indonesia. Therefore, it appears reasonable to concentrate on the final two philosophies: New Modernism and Sustainable Intensification.

2.1 New Modernism/Industrial Forestry

The argument of the new modernist is that by using the very best techniques available it will be possible to provide our wood raw material requirements from a reduced land area. This approach focuses primarily on the supply end of the

forest-wood chain and maximising what can be produced from the land using a very technological approach.

As discussed above much of the increasing demand for wood is being provided by planted forests. These planted forests are intensively managed, have a high input/high output approach making use of increased fertiliser input, improved genotypes of fast-growing trees (often deployed as clones), and potentially transgenic material. In agriculture the approach had led to transgenic crops being routinely grown (typically in soy, cotton, maize and rapeseed) and although transgenic trees are less common in forestry, they are now being commercially planted in, for example, China (poplar) and Brazil (eucalyptus). The New Modernism approach has been adopted by most of the intensively managed planted forests that have been developed in the past few decades and which are currently helping to provide the world's increased demand for wood. Its proponents argue that it is more sustainable overall because it is focussed on a smaller productive area and helps protect the world's natural forests (Gladstone and Ledig 1990).

Some of the most impressive developments in a very scientific approach to increasing production have taken place in countries with a relatively recent history of planted forest management such as Brazil, Chile and New Zealand. Campinhos (1999) discusses the successful development of planted eucalyptus forests around the world and, in particular, the use of clones of good hybrids of *E. grandis* and *E. urophylla* by the Aracruz Celulose S. A. Company. In Brazil, the productivity of four million ha of eucalyptus forests has tripled in the 35 years since the 1970s as a result of intensive research, improved operations (i.e. site preparation, fertilization, weed and pest control), improved seed selection and deployment of clonal material (Goncalves et al. 2008). Fast growing species that can be managed on short rotations offer significant advantages and in many tropical and subtropical regions eucalyptus is the preferred genus because:

1. It adapts well to different ecosystems
2. Naturally occurring native populations already exist
3. It matures quickly and is well shaped
4. Species can be crossed to produce hybrids with added vigour and different wood properties
5. It can be cloned at species and hybrid level
6. It produces wood with good properties for fibre, sawn-timber, chipboard, charcoal, posts and civil construction

Demand for eucalyptus wood has grown by over 10 % per year since 1982 and has been responsible for a shift in pulp production from temperate and sub-temperate to tropical and sub-tropical countries. Countries planting eucalyptus are Brazil, India, Spain, Portugal, South Africa, Angola, China, Ethiopia, Chile, Uruguay and Argentina with rotation lengths of 5–25 years.

The other genus that has been responsible for the large increase in clonal forestry, particularly in the Southern Hemisphere (New Zealand, Australia, Chile and South Africa) is pine (Sutton 1999). Pine and eucalyptus are particularly popular genera because of the choice of a wide genetic base, rapid growth under a range of

environmental conditions and the availability of technology to grow them quickly and cost-effectively. Despite the huge increase in eucalyptus and pine planting the supply is still not keeping pace with demand (e.g. Barreiro and Tomé 2012) leading to increasing prices. Haynes (2007) suggests that these increases in stumpage prices were the encouragement for systematic forest management, shortened rotations and practices designed to speed development of well managed forests in the USA. Slowing of the price trend in the 1990s reflected the growing importance of managed forests with higher volumes per ha. The recent increase again in global prices should continue to encourage owners to manage their forests more intensively. Therefore, we should anticipate a large increase in both harvest and inventory volumes although these managed forests will remain a small part of the total global forest base. Haynes (2007) concludes that the majority of forests will be lightly managed, if at all, while a small minority will be heavily (or actively) managed and provide the bulk of world timber needs.

There are concerns in the sector whether management practices designed to improve sustainability may be discouraging for owners because of cost and reduced financial return. The key question is whether increasing productivity is compatible with long-term sustainability. The problems with the New Modernist approach is that it requires high inputs (energy, fertiliser, etc.) so it may struggle to have a long-term future, particularly if the cost of inputs increases at a faster rate than the value of outputs. Social and environmental pressures may also limit the type and intensity of practices that can be employed (e.g. the use of herbicides and pesticides, and clearcut harvesting).

2.2 Sustainable Intensification

This is an idea that first developed in agriculture (Pretty 1997) and focusses much more on the whole chain. The argument is that if all the knowledge we have is implemented in the management of forests then it is possible to boost yields and to bring marginal areas into production without compromising the long term sustainability of the forest. It, therefore, addresses some of the concerns over the New Modernist approach by attempting to integrate a wide range of methods and techniques to manage pests, nutrients, soil and water (Table 2). It is a system that relies heavily on the engagement of all participants and the careful integration of a range of techniques and methods.

It is not as straightforward to implement as the New Modernist approach and has yet to be implemented on any scale. The concept of High Yield Forestry introduced by the Weyerhaeuser Company (Heninger et al. 1997) approaches the concept through use of growth and yield studies and computer simulations, tree improvement, tree propagation, forest regeneration and silvicultural methods while at the same time maintaining soil productivity and biodiversity. This is the system of management that has been commonly used in many parts of the industrialized world with clearly defined productivity and environmental targets. However, Sustainable Intensification relies much more on managing the forest as part of the ecosystem

Table 2 Comparison of different forest types

	Industrial forestry (New modernism)	Low input forestry	Sustainable intensification forestry
Forest size	Extremely large (thousands of hectares)	Generally small scale forestry	Mixture of scales from small to industrial
Ownership	Corporate	Individual	Mix of ownership
Fertilizer	High input of industrial fertilizer	None unless certified organic	Avoid fertilizer and rely on silviculture, agroforestry, etc.
Pest control	Chemical pesticides	No chemical pesticides	Use integrated pest management
Biodiversity impact	Reduced	Enhanced	Stable
Yield	High	Low	High but probably lower than industrial forestry
Cost	Low	High	Potentially lower than industrial forestry

and depends heavily on understanding the biological processes at work and utilising these to increase productivity and to reduce reliance on pesticides and fertilisers. The closest expression of this philosophy is contained through various third party certification organisations such as FSC (FSC 2002) and (PEFC 2010), although the focus is on maintaining social and environmental benefits and there is no focus on encouraging intensification of production. In addition the FAO outline how plantation forests when sustainably managed can provide a range of social, environmental and economic benefits particularly in the developing world (FAO 2010b). Sustainable Intensification, therefore, appears to fall somewhere between the philosophies of High Yield forestry and Forest Stewardship in that it seeks to apply many of the principles of Forest Stewardship to increase productivity.

A further difficulty for the Sustainable Intensification approach is the lack of research on the whole system. Individual components of the methodology have been studied in detail but there have been few attempts to date to pull everything together and to determine what is possible both practically and economically (for an attempt to identify knowledge gaps for real sustainable forest management see Hickey and Innes 2005). Therefore, much of our knowledge of such systems has to come from agriculture where considerably more work has been undertaken and where systems are being implemented (e.g. Tilman et al. 2011; Godfray et al. 2010).

2.3 *Forest Management*

The key to increasing productivity will be through forest management. There have been a huge numbers of papers and books on all aspects of the management of planted forests (e.g. Evans 2001, 2009). The difficulty is that planted forest

management is relatively recent and there is little experience of managing these forests over multiple rotations or of fully implementing the many techniques and approaches required to increase productivity in a sustainable manner. However, the evidence that does exist suggests that forests can be managed over multiple rotations and no fertilizer input with no loss of productivity (Woollons 2000; Evans 2009

In the past there has been a tendency to adopt four main management approaches to forestry but this is now being supplemented by forestry for biomass (Duncker et al. 2012). These are as follows with increasing levels of management intensity and inputs:

1. Forest nature reserve: Unmanaged forest to allow development of natural processes without human intervention.
2. Close to nature: Produce timber by mimicking or emulating natural processes
3. Extensive management with combined objectives: Combine production and ecological objectives at the stand level.
4. Intensive even-aged planted forests: Optimise wood production.
5. Short rotation forestry for biomass production: Produce the highest amount of wood biomass

Intensive even-aged planted forests and short rotation forestry for biomass fit the Industrial Forestry (New Modernist) approach, whereas the close to nature and extensive management with combined objectives forestry are closer to the Sustainable Intensification approach. However, for Sustainable Intensification to take place and be effective there will need to be a synthesis between the approaches.

However, there are other difficulties. In many countries the difficulty will be competing with imported timber from other parts of the world where costs may be lower and/or productivity higher. This may result in a divergence in forest management between public and private forestry such as has occurred in the Pacific Northwest of the US and New Zealand. Public forests will tend to be managed on longer rotations mainly (or in some cases exclusively) for environmental and social benefits with low inputs and potentially lower costs (e.g. much more use of natural regeneration) while private forestry will use shorter rotations and more intensive management. This tendency to zoning could have important impacts on the long-term sustainability of forestry and the ability of forestry to supply the increased wood production required.

There will clearly be a requirement for a number of management operations to be applied for the Sustainable Intensification approach to be successful. It will rely heavily on methods for reducing inputs, costs and for optimising management and the value of products produced:

1. Increased use of natural regeneration where possible.
2. Increased use of mixtures or agroforestry in order to maintain productivity without increased use of fertiliser (e.g. inter-cropping with legumes: Sankaran et al. 2005)
3. Adoption of techniques for integrated pest management in order to reduce the use of pesticides
4. Increased use of modern technologies for optimizing management inputs (e.g. targeting fertilizer use where most required) and the value of the products recovered from the forest. This is discussed in more detail in the following sections.

2.4 Climate Change and Threats to Forests

A major concern for future forestry and managing the increasing demand for wood is the threats from abiotic and biotic hazards and, in particular, how these will change with a changing climate (Lindner et al. 2010). Sedjo (2010) raises the question as to whether trees can migrate fast enough with climate change. The evidence is that many species will struggle (Pearson 2006; Zhu 2012) and some tree species are likely to “die back”. The interior of continents will become drier during the summer increasing the probability of drought and winters are likely to be milder in many places increasing the likelihood of problems from pests because their numbers are less affected by mild winters. For example, there has been a huge recent outbreak of mountain pine beetles in Western Canada that is probably due to milder winters (Kurz et al. 2008). Overall climate change is expected to increase the frequency and severity of disturbance (e.g. Dale et al. 2001; Gardiner et al. 2010).

Historically, much of the world’s timber supply came from the natural forests of North America, Russia and northern Europe but now the move is towards planted forests in south-east Asia, South America and Equatorial Africa. Global climate change that threatens and puts pressure on northern latitude forests is likely to hasten this transition. Potentially timber will be more abundant with an increased area of planted forests and faster growth rates (longer growing seasons and warmer temperatures) but forestry may no longer be profitable in some areas due to increasing levels of disturbance.

Another concern is the increasing use of clonal material in many planted forests. For example, Aracruz Celulose S. A. relies on clones of good hybrids of *E. grandis* and *E. urephylla* and there is a potentially high risk of major disturbance if the particular clones chosen are not adapted to a particular pest and are highly susceptible. We already know that some eucalyptus clones are more susceptible to abiotic risks such as wind damage (Garcia 2011). The focus on a small number of clones also runs the risk of reducing the genetic base for future improvement. A mosaic distribution of different clones at sites is recommended to reduce the risk associated with low genetic variability and of poor matching of a particular clone to a particular site (DeBell and Harrington 1993).

2.5 Substitution

An alternative to increasing the production of primary wood is to substitute other materials for wood (Wolcott 2003), to use forest and mill residues to make wood composites (Maloney 1996) or to make better use of what material is available. For example, corewood (i.e. wood formed in the first 10–15 annual rings from the pith) can be used for the central portion of laminates, defect cutting and green-gluing of knotty timber can produce strong engineered timber, waste fibres from annual plants substituted for wood fibre (e.g. Yang et al. 2003) and the innovative combination of wood and other materials, such as cement, lime and plastics, can produce material

with combined benefits (Karade 2010). Haynes and Weigand (1997) suggested that there will be a reduced reliance in solid wood and an increasing reliance on engineered wood and recycled materials over the next 50 years. For example, advances in light timber frame construction, including the use of engineered wood products such as I-joists, means that the average house built today uses less wood per unit area than it did previously. At the same time the decline in available volume has meant that there has been a switch from just considering quantity and increased focus on value and increasing value (Whittenbury 1997; Murphy 1998). This means making use of low or variable quality wood, which is discussed in more detail later in this chapter.

A key question is what are the impacts of substitution on various measures of sustainability (Petersen and Solberg 2005)? Also can wood-based products incorporating other materials still offer the advantages of bio-materials but have a low enough impact on the environment. For example, particle boards which are increasing in global volume are usually produced using resins that rely on formaldehyde as a solvent and there has been a huge effort to reduce the in-service emissions of formaldehyde. Finally, if there is an increasing reliance on recycled or waste biomaterials and less critical requirements placed on virgin wood and fibre, what are the implications for forest management practice? Will forest management no longer be profitable and will such a change direct managers to a very low input type of forestry. These topics will be discussed at the end of the chapter.

3 Integration of the Wood Supply Chain

Although increasing the volume of wood produced is one option for meeting increasing demand another approach is to make more optimal use of the material that is produced. Murphy et al. (2010) state that: “Optimal allocation of the wood fibre resource is vital if wood and bio-energy are to obtain the material most suited to their needs and wood suppliers are to obtain the best return for their investment in forest land”. They found 50 % gains in net value recovery using optimised solutions. More modest gains of 3–7 % were obtained by Mitchell (2004),but higher values have been obtained for New Zealand and Chilean forests (Murphy et al. 2010). Optimization is currently a means for adding value to forest processing but it could also help to satisfy the increasing demand for wood material by reducing wastage and allocating material to the most appropriate end-use. The techniques for rapidly and non-destructively measuring wood properties at all stages of the wood chain and for calculating the best allocation strategies for the complex forest-wood chain are now available due to advances in operations research and artificial intelligence.

Focussing on optimization will also help to re-establish and improve the link between growers, processors and end users. Currently there appears to be little understanding by growers of the detailed requirements of the final end-users and end-users have little comprehension of what is both physically and economically

possible by growers (Moore 2012). Processors, who are in the middle of the supply chain, could be engaged in feeding information in both directions along the chain but are often primarily engaged in maximising volume throughput and recovery and pay less attention to ensuring the material properties of their products are specific to the intended end-use. Researchers and breeders have also focussed on increasing volume production and in the future it is going to be vital that improvements in genetics and silviculture need to be focussed not only on productivity but on the suitability of the wood for a particular end-use. The question is whether the current wood production model can survive with improvements in the connectivity of the supply chain or whether we need fully vertically integrated companies or partnerships. This is essentially the choice that needs to be made between the New Modernist and the Sustainable Intensification approaches and it is most likely that different approaches will be required in different parts of the world and in different parts of the wood market.

3.1 Optimisation

In order to improve the efficiency of the forest-to-customer supply chain it is possible to make use of management science techniques. Such techniques have been used to support different aspects of forest management since at least the 1960s (Bare et al. 1984; Martell et al. 1998). These include strategic forest management at the scale of thousands of hectares with long time scales through to operational management at small spatial scales and with relative short term time scales. At the operational level, techniques have been applied to the selection of stands to be harvested (e.g. Papps and Manley 1992), cross-cutting of tree stems into logs (e.g. Deadman and Goulding 1979; Eng et al. 1986; Lembersky and Chi 1986), the allocation of these logs to various mills in order to satisfy demand (e.g. Mendoza and Bare 1986), the transport of these logs to their destination (e.g. Weintraub et al. 1995; Murphy 2003) and the processing of these logs in order to maximise value and/or to produce products with certain characteristics (e.g. Todoroki and Rönnqvist 2002).

In many of these studies linear or integer programming techniques have been used and the focus has been on optimizing a particular component of the forest-to-mill supply chain. However, this is unlikely to yield the same benefits as global optimization of the whole supply chain (Faaland and Briggs 1984; Mendoza and Bare 1986). In addition, optimization studies have tended to focus on external tree attributes such as size (diameter and height), shape (taper, sweep and circularity) and the characteristics of branches (number, size, and angle). However, end-users requirements and product grading specifications are shifting from being based on visual characteristics (e.g. ring width, stem shape, branch size) to being based on material properties such as strength, stiffness, fibre dimensions, and density. Fortunately within the last decade a large number of techniques have become available, which enable some of these properties to be measured non-destructively and rapidly at different points in the supply chain (see section below).

While classical optimization techniques such as linear or integer programming are good at producing exact and accurate solutions to problems that can be formulated in exact mathematical terms, they are not designed to work with inaccurate, noisy or complex data. Neither are they suitable for problems which change over time. Furthermore, the sheer size of the search-space that must be explored for large problems often renders the techniques intractable on many practical problems. In many cases, the use of linear programming techniques in forest management problems has required a considerable simplification of management objectives and constraints (Garcia 1984). The field of meta-heuristics is a relatively new field which although not guaranteeing optimality, reliably achieve "good enough, fast enough" solutions to problems. In general they are simple to implement, computationally cheap, robust to changes in data and have been proven to be highly effective. They are particularly suited to problem areas such as transportation and inventory management where the data being used to attempt to solve a problem is in itself an estimation and the problem has many variables and constraints which rule out any brute-force type approach to finding a solution (Lourenco 2005).

Heuristic techniques are just now being applied to the forestry sector, such as the use of applied tabu-search algorithms for locating machinery for optimizing forest harvesting (Diaz-Legues 2007) and simulated annealing used to develop solutions for balancing harvesting targets against the risk of wind damage (Zeng et al. 2007). Further developments are inevitable in helping to optimize the forest-to-customer supply chain by ensuring that the right material is supplied to the right customer in a cost effective manner and that efficient use is made of capital and distribution networks (Frayret et al. 2007). Ultimately, this could lead to build-to-order supply chains which can deliver considerable cost savings and improved customer satisfaction (Mansouri et al. 2012).

3.2 Wood Property Measurement

Forest Inventory

In order to improve the allocation of wood material in the future it is essential that there is detailed information on the properties of the wood available and this information is linked to material as it passes along the chain. Fundamental information required is tree size, numbers and species, but increasingly information on quality features is also required. New remote sensing techniques now allow information on the forest resource to be obtained in extraordinary detail. In particular, recent developments in airborne laser scanning technology (LiDAR – Light Detection and Ranging) have enabled information on tree heights, crown width, and stand density to be obtained (Hyyppä et al. 2012; Pirotti et al. 2010; Suárez et al. 2008 from virtually (>95 %) of all trees in the forest. Airborne LiDAR in combination with field sampling is now seen as an effective method for operational forest inventories (e.g. Andersen et al. 2006; Wynne 2006). In addition to providing this kind of detailed

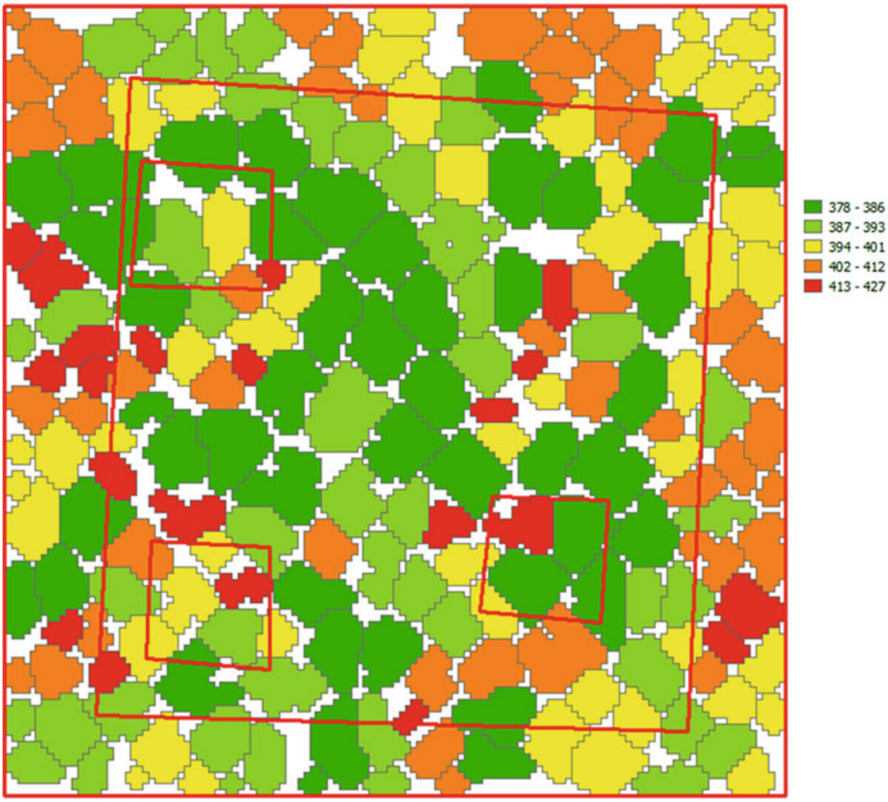

Fig. 3 Map of individual Sitka spruce trees in Aberfoyle Forest, Scotland with predicted wood densities (kg m^{-3}). Based on airborne LiDAR measurements and the wood density model of Gardiner et al. (2011), Suárez (2010) (Courtesy of Juan Suarez, Forest Research)

mensurational information at the individual tree or stand scale, LiDAR allows the mapping of structural differences in the forest at a very fine scale (metres) and over very large (>100 km) areas. Such surveys have already been conducted or are in progress for a number of countries. Much of the current research focus is now directed towards the prediction of internal wood properties from metrics obtained using LiDAR (e.g. van Leeuwen et al. 2011; Fig. 3).

In addition to airborne LiDAR, Terrestrial Laser Scanning (TLS) technology has shown the potential to provide information on tree and stand characteristics such as stand density, tree diameter, height and crown shape (Dassot et al. 2011); stem profiles (Aschoff and Spiecker 2004), and some branch attributes (Schutt et al. 2004; Keane 2007). Stem data collected by terrestrial scanners can also be stored in standard harvester data formats (e.g., StanForD: Skogforsk 2011), and used to assist forest managers with optimizing harvest scheduling and cross-cutting into logs (Keane 2007).

Fig. 4 Measuring wood stiffness in a standing tree using a hand-held acoustic tool (photograph B. Gardiner)

Acoustic Testing

The use of stress (acoustic) waves to determine the properties of solids is a well-established technique in the field of materials science (Kolsky 1963). Of particular value is the fact that the stress wave velocity in a material is proportional to the material stiffness (modulus of elasticity) and inversely proportional to its density. This technique has been applied to wood since the 1950s (Jayne 1959), initially in the laboratory, but more recently as commercially-available machines for strength grading sawn structural timber in a mill.

Stress wave techniques have also been applied to identify those logs and standing trees with the higher stiffness wood necessary to produce high quality structural timber (e.g. Ross et al. 1997; Tseheye et al. 2000; Wang et al. 2007a; Auty and Achim 2008). In recent years a large number of studies involving the use of stress waves to measure the wood stiffness in standing trees and logs have been undertaken, in part because the forest products industries are under increasing economic pressure to maximise the value obtained from the resource (Wang et al. 2007b). A number of portable tools have been developed to make these measurements (e.g. Fig. 4) and their operating principles are described in Huang et al. (2003) and Huang (2005). Results from numerous studies show that there is a strong correspondence between stress wave velocity measurements made on standing trees and those made on logs (e.g. Wang et al. 2005; Moore et al. 2013), and with these measurements and the yield of structural grade timber (Carter et al. 2005; Moore et al. 2013). Stress

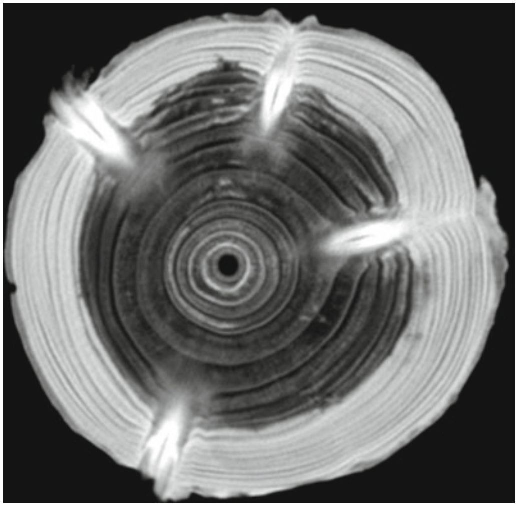

Fig. 5 X-ray scan of Sitka spruce log (3 mm slice) clearly showing heartwood, sapwood, growth rings and knots. Image obtained with a Somaton Esprit CT scanner (Siemens, Forchheim, Germany)

wave velocity measurements have also been use to segregate logs for veneer (Carter et al. 2005) and pulp production (Albert et al. 2002).

Measurement of the stress wave velocity in standing trees within the forest is also of value to forest owners as it not only allows the resource to be characterised with respect to wood properties (e.g. Moore et al. 2009), but it also allows the effect of different silvicultural treatments, such as thinning, to be evaluated for their impact of wood stiffness without having to fell the trees (e.g. Lasserre et al. 2005. The relationships between timber stiffness and stress wave velocity measurements can also be used to inform tree breeding efforts focussed on improving this timber property (e.g. Kumar 2004; Cherry et al. 2008; Vikram et al. 2011). Recent developments have seen acoustic measurements implemented in the cutting head of harvesting machines (Amishev and Murphy 2008), which provides the possibility of thinning selectively on the basis of the wood stiffness of trees and optimise cross-cutting (bucking) of trees during harvesting. Such cross-cutting can be linked with forest inventory data (see section above) and customer requirements to cut logs for different end products in the forest rather than later in the mill.

X-Ray CT Log Scanning

Interest in within-tree distributions of knot/branch and wood properties has increased in recent decades and is driven by the desire to achieve greater value recovery from logs. However, historical methods for analysing the internal tree stem structure were destructive and time consuming. Since the pioneer work performed in Sweden (Lindgren 1991; Grundberg and Grönlund 1997), the use of X-ray CT scanners enables more detailed investigation of the internal structure of the tree stem (see Fig. 5) in order to assess the wood density variations, and the shape and size of the included part of the branches (knots) (Longuetaud et al. 2005; Sepulveda et al. 2002).

The knowledge of the distribution of heartwood and sapwood in trees stems is also important as their physical and technological properties often differ in terms of colour (Münster-Swendsen 1987; Espinoza et al. 2005), natural durability (Cruz et al. 1998; Björklund 1999; Kärenlampi and Riekkinen 2003), impregnation properties and durability (Wang and De Groot 1996), and moisture content (Fromm et al. 2001). The use of X-ray log scanners allows the measurement and the modelling of the within tree stems distribution of sapwood (Longuetaud et al 2007) even when there is no difference in colour between heartwood and sapwood (e.g. Norway spruce).

X-ray scanners have been available for boards for a number of years and in recent years there has been considerable research into the development of commercial X-ray scanners for logs, with the first machines now available (e.g. www.microtec.eu).

Growth and Wood Properties Modelling

The use of robust models is a key component of forest management where they are used to support activities such as the development of silvicultural regimes and forecasting future timber yields. For a long time, forest models focused on the prediction of stand and tree-level attributes, such as dominant height, basal area and volume or tree diameter at breast height as a function of age, stand density and site quality (Clutter et al. 1983). Data collected from empirical studies were used to construct yield models and tree and stand-level growth models (e.g. Houllier et al. 1991; Goulding 1994). The connections of these models with wood quality were often very limited: the main information that they provided about the yields and attributes of wood products was related to the size of the trees (for the mean and dominant trees with stand models or for every tree in the stand with tree models: Lemoine 1991), tree taper through stem profile equations (e.g. Newnham 1992) and branch models (e.g. Grace et al. 1999). Decision support systems such as StandPak (Whiteside 1990) integrated several of these models together in order to understand the impacts of forest management on log quality and stand value. In some cases results from sawing studies on logs of known quality were incorporated into these decision support systems, which enabled product quality to be linked back to forest management (e.g. Whiteside and McGregor 1987).

More recently, the need for management tools that integrate both growth and wood quality information led to a new generation of more detailed models which use stand– and tree-level information to predict wood properties and quality attributes such as branch characteristics (i.e. number, position, size, insertion angle and status), fibre dimensions, wood density, microfibril angle, and wood stiffness (e.g. Mitchell 1988; Maguire et al. 1991; Briggs 1992; Leban et al. 1997; Houllier et al. 1995; Longuetaud et al. 2007; Gardiner et al. 2011; Auty et al. 2013; Meredieu et al. 1998). Together these stem and wood properties are important determinants of the quality of end-products in terms of characteristics such as strength (bending and crushing), stiffness, colour, shrinkage and

distortion. End product quality can either be modelled empirically (e.g. Johansson et al. 2001) or numerically from information on key wood properties (e.g. Ormarsson et al. 1999). These models have mostly been developed for coniferous trees but are now being developed for fast-growing hardwoods such as eucalyptus (Downes et al. 2009) and poplar (Jiang et al. 2007) and a number of tropical species being grown in planted forests (e.g. Kokutse et al. 2010; Perera et al. 2012). These models operate at the tree level but may be either average tree models, distance-independent or distance-dependent individual tree models and are often used in conjunction with sawmill conversion simulation systems (Vaisanen et al. 1989; Leban and Duchanois 1990; Barbour and Kellogg 1990; Briggs 1992; Leban et al. 1997) in order to provide a link between product recovery and different silvicultural strategies, raw material sources, or bucking and sawing patterns. This enables predictions of suitability for different end-products and product performance to be made prior to being put in-service rather than being discovered in-service. It also makes it possible to study the utilisation of timber in terms of alternative decisions in the whole forest-wood chain.

The Forest Resource

The traditional description of the forest resource emphasises factors such as available wood volume, and trees size and status. For the future, information is required on internal stem properties including the property differences between various types of stands, trees and parts of trees. Such information can be provided with measurements on the standing trees using non-destructive methods as discussed above or by model estimation using traditional or extended monitoring data as inputs. Recently the concept of Regional Resource Databases has been developed, to support optimal allocation and processing of available wood for different products (Grahn and Lundqvist 2008; Lundqvist et al. 2008). Forest resources large enough to be representative of a region or the resource catchment of a mill are simulated, providing information about the properties and volumes of trees, parts of trees and potential products from the trees. The simulation is performed in a stepwise manner with a set of integrated models, starting with measured breast height diameters and stand data, estimating (i) the age, height and taper of the tree, (ii) the interior growth pattern, (ii) the wood and fibre properties at different heights (wood density, heartwood, knot properties, fibre dimensions, etc.), and (iii) the properties and volumes of parts of the tree related to potential products (pulpwood logs, sawlogs, parts which will become sawn products and sawmill chips, etc.).

The forest, therefore, becomes the warehouse in an integrated processing system. Modern measurement methods and IT systems allow continual updating of the wood available or moving through the system and the properties of this material. Artificial intelligence can then optimize this flow of material against a set of clearly defined targets and to adjust processes as the material properties or availability changes (e.g. Frayret et al. 2007).

4 Implications for Forestry

Wood is in a prime position to be one of the materials of choice in the twenty-first century with its combination of availability, sustainability and low cost. However, to ensure that this vision is realised a big shift in the way the whole forest wood chain operates has to take place. All parts of the process have to be seen as integral and not just as individual components with only a limited local importance. It probably means a tendency to more companies operating across the entire chain from forest to end-product or much closer strategic partnerships in order for knowledge to be freely shared between all parts of the chain.

In order for increasing demand for wood products to be met there has to be a twofold approach. Firstly, there needs to be increased production through increased use of planted forests and increased productivity of existing planted forests as we discussed at the beginning of the chapter. This requires the use of the very latest techniques and an integrated approach to management in order to boost productivity without sacrificing long-term sustainability. Forests can no longer be managed with a single focus, such as maximizing volume, without taking into consideration the impact on soil status, water quality, biodiversity, etc. The result is almost certainly a separation of forest types with increased emphasis on identifying those forests (or areas to be reforested or afforested) that have the potential to supply the increasing demand and those forests that are unable to do so for environmental, social or economic reasons and which will be managed with a focus on something other than wood production.

Secondly, there needs to be much better information available on the forest resource and the properties of this resource and the properties of material within the chain comprehensively and continuously tracked (see an idealised concept for an optimized wood chain in Fig. 6). The forestry sector is significantly behind other

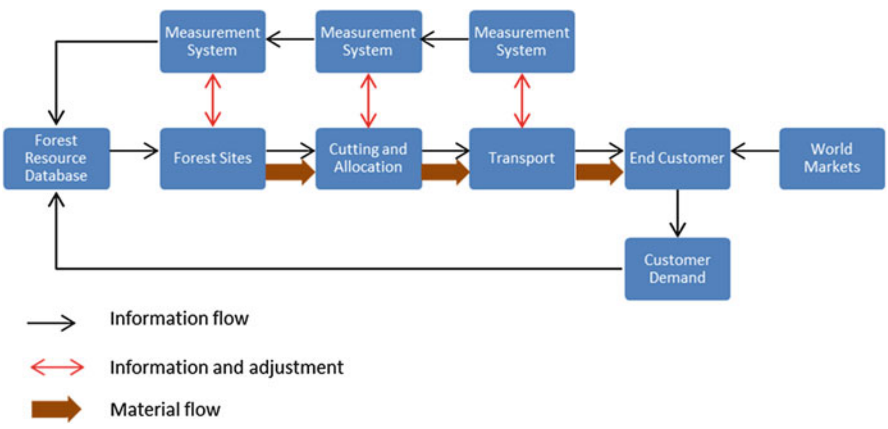

Fig. 6 Stylised flow diagram of an integrated and optimised wood chain

sectors in its knowledge of the material it is processing and many decisions on material suitability are made much later than is ideal. In addition there is limited feedback at each processing stage which is required to inform decision making early and later in the chain to adjust and match end-product requirements and material availability. However, the tools for characterizing the material properties, to track these properties, to transfer and manage this information are all already available. The difficulties of implementing such a plan are partly the tight margins that operate in the forest products sector and especially for growers but also the innate conservatism in an industry that has focussed too often on volume and has learnt to adapt and make-do with whatever material is available. However, unless the sector changes to one primarily focussed on matching end-product requirements against raw material properties it will continue to struggle to compete with other sectors producing material to much tighter specifications.

Alongside all this are unknowns such as changing levels of risk, changes in economics and market requirements. In order to deal with these challenges forestry and the silvicultural systems will need to be flexible and resilient (Moore 2012). This is enormously difficult because competition is fierce and global and the temptation is to find the solutions that provide the highest profit margins. These have a tendency to be focussed on single species and a limited set of silvicultural systems but the dangers of such an approach are evident in the high levels of damage that have been recently experienced in Europe and North America from both biotic and abiotic agents. Silviculture needs to be dynamic and flexible enough to incorporate these changes and to anticipate the problems of the future and to adapt the management to these threats before rather than after events.

5 Summary and Conclusions

For the forests of the world to continue to be able to provide the increasing demand for wood and wood-based products requires an increasing reliance on existing and new planted forests. These forests will need to be managed using the very latest understanding of the biological processes at work in forest ecosystems in order to increase their productivity while maintaining their sustainability similar to the requirement for crop production (FAO 2009b). In addition the silvicultural systems will need to be designed to be resilient and to incorporate risk mitigation strategies under a changing climate.

Wood fibre produced from the worlds' forests needs to be used in a more optimized manner with material matched to end-use requirements and wood-based products being designed to utilise the mix of virgin and recycled material that will be available in the future. To do this requires a much greater level of integration of the forest-wood chain and proper exchange of information on material dimensions and properties between all stages of the process.

The knowledge and tools for implementing systems to increase the productivity of our forests and to make the best use of the material they produce are already

available. The question is whether the sector can respond to the challenge and modernise the system in a way that allows wood-based products to become the materials of choice in the future. It will require investment, co-operation of all stakeholders from growers to processors and researchers, and hard decisions on the management focus for every forest. With increasing pressure on land-use from urbanisation and agriculture the forest-based sector has to make much more targeted and efficient use of the land it has available in order to continue to provide the world's wood needs.

References

Albert DJ, Clark TA, Dickson RL, Walker JCF (2002) Using acoustics to sort radiata pine pulp logs according to fibre characteristics and paper properties. Int Forest Rev 4(1):12–19

Amishev D, Murphy GE (2008) Implementing resonance-based acoustic technology on mechanical harvesters/processors for real-time wood stiffness measurement: opportunities and considerations. Int J Forest Eng 19(2):48–56

Andersen H-E, Reutebuch SE, McGaughey RJ (2006) A rigorous assessment of the height measurements obtained using airborne lidar and conventional field methods. Can J Remote Sens 32(5):355–366

Aschoff T, Spiecker H (2004) Algorithms for the automatic detection of trees in laser scanner data. ISPRS 36:66–70

Auty D, Achim A (2008) The relationship between standing tree acoustic assessment and timber quality in Scots pine and practical implications for assessing timber quality from naturally regenerated stands. Forestry 81(4):475–487

Auty D, Gardiner B, Achim A, Moore JR, Cameron AD (2013) Models for predicting microfibril angle variation in Scots pine. Ann Forest Sci. doi:1007/s13595-012-0248-6

Barbour RJ, Kellogg RM (1990) Forest management and end-product quality-a Canadian perspective. Can J Forest Res 20(4):405–414

Bare BB, Briggs DG, Roise JP, Schreuder GF (1984) A survey of systems analysis models in forestry and the forest products industry. Eur J Oper Res 18:1–18

Barreiro S, Tomé M (2012) Analysis of the impact of the use of eucalyptus biomass for energy on wood availability for eucalyptus forest in Portugal: a simulation study. Ecol Soc 17(2):14, http://dx.doi.org/10.5751/ES-04642-170214

Björklund L (1999) Identifying heartwood-rich stands or stems of *Pinus sylvestris* by using inventory data. Silva Fenn 33:119–129

Briggs DG (1992) Models linking silviculture, wood quality and product value: a review and example for US coastal Douglas-fir. In: IUFRO all division 5 conference forest products, Nancy, 23–28 Aug 1992. ARBOLOR Bd, pp 285–294

Campinhos E (1999) Sustainable plantations of high-yield shape eucalyptus trees for production of fiber: the Aracruz case. New Forest 17:129–143

Carle J, Holmgren P (2008) Wood from planted forests: a global outlook 2005–2030. Forest Prod J 58(12):6–18

Carter P, Briggs D, Ross RJ, Wang X (2005) Acoustic testing to enhance western forest values and meet customer wood quality needs. PNW-GTR-642, productivity of western forests: a forest products focus. USDA Forest Service, Pacific Northwest Research Station, Portland, pp 121–129

Cherry ML, Vikram V, Briggs D, Cress DW, Howe GT (2008) Genetic variation in direct and indirect measures of wood stiffness. Can J Forest Res 38:2476–2486

Clutter JL, Forston JC, Pienaar LV, Brister GH, Bailey RL (1983) Timber management, a quantitative approach. Wiley, New York, p 333

Cruz H, Nunes L, Machado JS (1998) Update assessment of Portuguese maritime pinetimber. Forest Prod J 48:60–64
Dale VH, Joyce LA, McNulty S, Neilson RP, Ayres MP, Flannigan MD, Hanson PJ, Irland LC, Lugo AE, Peterson CJ, Simberloff D, Swanson FJ, Stocks BJ, Wotton BM (2001) Climate change and forest disturbances. BioScience 51:723–734
Dassot M, Constant T, Fournier M (2011) The use of terrestrial LiDAR technology in forest science: application fields, benefits and challenges. Ann Forest Sci 68:959–974. doi:10.1007/s13595-011-0102-2
Deadman MW, Goulding CJ (1979) A method for the assessment of recoverable volume by log types. N Z J Forest Sci 9:225–239
DeBell DS, Harrington CA (1993) Deploying genotypes in short-rotation plantations: mixtures and pure cultures of clones and species. Forest Chron 69:705–713
Diaz-Legues A, Ferland JA, Ribeiro CC, Vera JR, Weintaub A (2007) A tabu search approach for solving a difficult forest harvesting machine location problem. Eur J Oper Res 179:788–805
Downes GM, Drew D, Battaglia M, Schulz D (2009) Measuring and modelling stem growth and wood formation: an overview. Dendrochronologia 27:147–157, 2009
Duncker PH, Barreiro S, Hengeveld G, Lind T, Mason W, Ambrozy S, Spiecker H (2012) Classification of forest management approaches: a new methodological framework and its applicability to European forestry. Ecol Soc 17(4):50, http://dx.doi.org/10.5751/ES-05066-170450
Eng G, Daellenback HG, Whyte AGD (1986) Bucking tree-length stems optimally. Can J Forest Res 16:1030–1035
Espinoza GR, Hernandez R, Condal A, Verret D, Beauregard R (2005) Exploration of the physical properties of internal characteristics of sugar maple logs and relationships with CT images. Wood Fiber Sci 37:591–604
Evans J (ed) (2001) The forest handbook, volume 2: applying forest science for sustainable forest management. Blackwell Science, Oxford, p 382, ISBN 0-632-04823-9
Evans J (ed) (2009) Planted forests: uses, impacts and sustainability. Published jointly by FAO and CAB International. Wallingford, UK. ISBN 978-1-84593-564-1
Faaland B, Briggs D (1984) Log bucking and lumber manufacturing using dynamic programming. Manag Sci 30:245–257
FAO (2007) Global wood and wood products flow: trends and perspectives. Advisory Committee on Paper and Wood Products, Shanghai, 6 June 2007
FAO (2009a) State of the world's forests 2009, Rome, Italy. Also available at www.fao.org/docrep/011/i0350e/i0350e00.HTM
FAO (2009b) Increasing crop production sustainably: the perspective of biological processes, Rome, Italy. Also available at http://www.fao.org/docrep/012/i1235e/i1235e00.htm
FAO (2010c) Global forest resources assessment 2010: main report. Forestry Paper 163, Rome, Italy, 378 pp. Also available at http://www.fao.org/forestry/fra/fra2010/en/
FAO (2010b) Planted forests in sustainable forest management: a statement of principles, Rome, Italy, 16pp. Also available at http://www.fao.org/docrep/012/al248e/al248e00.pdf
FAO (2012) The state of food insecurity in the world, Rome, Italy, 65pp. Also available at http://www.fao.org/docrep/016/i3027e/i3027e00.htm
Fenning TM, Gershenzonand J (2002) Where will the wood come from? Plantation forests and the role of biotechnology. Trends Biotechnol 20:291–296
Fenning TM, Walter C, Gartland KMA (2008) Forest biotech and climate change. Nat Biotechnol 26:615–617
Frayret J-M, D'Amours S, Rousseau A, Harvey S, Gaudreault J (2007) Agent-based supply-chain planning in the forest products industry. Int J Flex Manuf Syst 19:358–391. doi:10.1007/s10696-008-9034-z
Fromm JH, Sautter I, Matthies D, Kremer J, Schumacher P, Ganter C (2001) Xylem water content and wood density in spruce and oak trees detected by high-resolution computed tomography. Plant Physiol 127:416–425

FSC (2002) FSC principles and criteria for forest stewardship. FSC-STD-01-001 (version 4-0) EN, Bonn, Germany, p 13. http://ic.fsc.org/download.fsc-std-01-001-v4-0-en-fsc-principles-and-criteria-for-forest-stewardship.315.pdf
Garcia O (1984) FOLPI, a forestry-orientated linear programming interpreter. In: Nagumo H, et al (eds) Proceedings IUFRO symposium on forest management planning and managerial economics. University of Tokyo, Japan, pp 293–305
Garcia J (2011) Biomechanics of young grown eucalypts trees and pulling test relationship. IUFRO 8.03.06 – Impact of wind on forests 6th international conference on wind and trees, Athens, 31 July to 4 Aug 2011
Gardiner B, Blennow K, Carnus J-M et al (2010) Destructive storms in European forests: past and forthcoming impacts. Final report to EC DG environment http://ec.europa.eu/environment/forests/fprotection.htm
Gardiner B, Leban J-M, Auty D, Simpson H (2011) Models for predicting the wood density of British grown Sitka spruce. Forestry 84(2):119–132. doi:10.1093/forestry/cpq050
Gladstone WT, Ledig FT (1990) Reducing pressure on natural forests through high-yield forestry. Forest Ecol Manag 35:69–78
Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Pretty J, Robinson S, Thomas SM, Toulmin C (2010) Food security: the challenge of feeding 9 billion people. Science 327:812–818
Goncalves JLM, Stape JL, Laclau J-P, Bouillet J-P, Ranger J (2008) Assessing the effects of early silvicultural management on long-term site productivity of fast-growing eucalypt plantations: the Brazilian experience. South Forest 70:105–118
Goulding CJ (1994) Development of growth models for *Pinus radiata* in New Zealand – experience with management and process models. Forest Eco Manag 69:331–343
Grace JC, Pont D, Goulding CJ, Rawley B (1999) Modeling branch development for forest management. N Z J Forest Sci 29:391–408
Grahn T, Lundqvist S-O (2008) Use of inventory data, simulation and regional resource databases for selection of wood to different end-products. In: Proceedings of sixth IUFRO workshop on modelling of wood quality, Koli, Finland, 9–13 June 2008
Grundberg S, Grönlund A (1997) Simulated grading of logs with an X-ray log scanner–grading accuracy compared with manual grading. Scand J Forest Res 12:70–76
Haynes RW (2007) Integrating concerns about wood production and sustainable forest management in the United States. J Sustain Forest 24(1):1–18
Haynes RW, Weigand JF (1997) The context for forestry economics in the 21st century. In: Kohn K, Franklin J (eds) Creating a forestry for the 21st century. Island Press, Washington D.C., U.S.A., pp 285–302
Heninger RL, Terry TA, Dobowski A, Scott W (1997) Managing for sustainable site productivity: Weyerhaeuser's forestry perspective. Biomass Bioenergy 13:255–267
Hickey GM, Innes JL (2005) Scientific review and gap analysis of sustainable forest management. Criteria and indicators initiatives: Forrex forest research extension partnership, Kamloops, B.C. Forrex Series 17 www.forrex.org/publications/FORREXSeries/FS17.pdf
Houllier F, Bouchon J, Birot Y (1991) Modelisation de la dynamique des peuplements forestiers: etat et perspectives. Rev Forest Fr 43:87–108
Houllier F, Leban J-M, Colin F (1995) Linking growth modelling to timber quality assessment for Norway spruce. For Ecol Manag 74:91–102
Huang C-L (2005) System and method for measuring stiffness in standing trees. Acoust Soc Am J 118(5):2763–2764
Huang C-L, Lindström H, Nakada R, Ralston J (2003) Cell wall structure and wood properties determined by acoustics: a selective review. HolzalsRoh– und Werkstoff 61:321–335
Hyyppä J, Yu X, Hyyppä H, Vastaranta M, Holopainen M, Kukko A, Kaartinen H, Jaakkola A, Vaaja M, Koskinen J, Alho P (2012) Advances in forest inventory using airborne laser scanning. Remote Sens 4:1190–1207. doi:10.3390/rs4051190
Ince PJ, Kramp AD, Skog KE, Yoo D, Sample VA (2011) Modeling U.S. forest sector trade impacts and expansion in wood energy consumption. J For Econ 17:142–156

Jayne BA (1959) Vibrational properties of wood as indices of quality. Forest Prod J 9(11):413–416
Jiang ZH, Wang XQ, Fei BH, Ren HQ, Liu XE (2007) Effect of stand and tree attributes on growth and wood quality characteristics from a spacing trial with *Populus xiaohei*. Ann Forest Sci 64:807–814. doi:10.1051/forest:2007063
Johansson M, Perstorper M, Kliger R, Johansson G (2001) Distortion of Norway spruce. Part 2. Modelling twist. HolzalsRoh– und Werkstoff 59:155–162
Jonsson R, Whiteman A (2008) Global forest product projections. Food and Agricultural Organization (FAO) of the United Nations, Rome
Karade SR (2010) Cement-bonded composites from lignocellulosic wastes. Constr Build Mater 24:1323–1330
Kärenlampi PP, Riekkinen M (2003) Prediction of the heartwood content of pine logs. Wood Fiber Sci 35:83–89
Keane E. (2007) The potential of terrestrial laser scanning technology in pre-harvest timber measurement operations. COFORD CONNECTS: Harvesting/Transportation No. 7
Kokutse AD, Stokes A, Kokutse NK, Kokou K (2010) Which factors most influence heartwood distribution and radial growth in plantation teak? Ann Forest Sci 67:407. doi:10.1051/forest/2009127
Kolsky H (1963) Stress waves in solids, 2nd edn. Dover, U.K., pp 213
Kumar S (2004) Genetic parameter estimates for wood stiffness, strength, internal checking, and resin bleeding for radiata pine. Can J Forest Res 34:2601–2610
Kurz WA, Dymond CC, Stinson G, Rampley GJ, Neilson ET, Carroll AL, Ebata T, Safranyik L (2008) Mountain pine beetle and forest carbon feedback to climate change. Nature 452:987–990
Ladanai S, Vinterbäck (2009) Global potential of sustainable biomass for energy. Report 013, ISSN 1654-9406. Swedish University of Agricultural Sciences Department of Energy and Technology, Uppsala, http://pub.epsilon.slu.se/4523/1/ladanai_et_al_100211.pdf
Lasserre J-P, Mason EG, Watt MS (2005) The effect of genotype and spacing on *Pinus radiata* [D. Don] corewood stiffness in an 11-year old experiment. Forest Ecol Manag 205:375–383
Leban JM, Duchanois G (1990) SIMQUA : modelling wood quality – New software –SIMQUA. Ann Sci Forest 47(5):483–493
Leban JM, Daquitaine R, Houllier F, Saint André L (1997) Linking models for tree growth and wood quality in Norway spruce. Part I: validation. IUFRO Working party S5.01-04, biological improvement of wood properties. Second workshop connection between silviculture and wood quality through modelling approaches and simulation softwares, Kruger National Park, South Africa, 26–31 Aug, pp 220–228
Lembersky M, Chi U (1986) Weyerhaeuser decision simulator. Interfaces 16:6–15
Lemoine B (1991) Growth and yield of maritime pine (*Pinus pinaster* Ait.): the average dominant tree of the stand. Ann Sci Forest 48:593–611
Lindgren LO (1991) Medical CAT-scanning: x-ray absorption coefficients CT-numbers and their relation to wood density. Wood Sci Technol 25:341–349
Lindner M, Maroschek M, Netherer S, Kremer A, Barbati A, Garcia-Gonzalo J, Seidl R, Delzon S, Corona P, Kolström M, Lexer MJ, Marchetti M (2010) Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. Forest Ecol Manag 259:698–709
Longuetaud F, Saint André L, Leban JM (2005) Automatic detection of whorls on *Picea abies* logs using an optical and an X-ray scanner. J Non-Destruct Eval 24(1):29–43
Longuetaud F, Mothe F, Leban JM (2007) Automatic detection of the heartwood / sapwood limit from stacks of CT images of Norway spruce logs. Comput Electron Agric 58(2):100–111
Lourenco H (2005) Logistics management: an opportunity for meta-heuristics. In: Rego C, Alidaee B (eds) Metaheuristic optimization via memory and evolution: Tabu search and scatter search. Kluwer Academic Publishers, Boston/Dordrecht/London, pp 329–35630
Lundqvist S-O, Grahn T, Olsson L et al (2008) Modelling and simulation of properties of forest resources and along the paper value chain. In: Proceedings of sixth IUFRO workshop on modelling of wood quality, Koli, Finland, 9–13 June 2008

Maguire DA, Kershaw JA, Hann DW (1991) Predicting the effects of silvicultural regime on branch size and crown wood core in Douglas-fir. Forest Sci 37:1409–1428
Maloney TM (1996) The family of wood composite materials. Forest Prod J 46(2):19–26
Mansouri-Afshin S, Gallear D, Askariazad MH (2012) Decision support for build-to-order supply chain management through multi objective optimization. Int J Prod Econ 135:24–36
Martell DL, Gunn EA, Weintraub A (1998) Forest management challenges for operational researchers. Eur J Oper Res 104:1–17
Mendoza GA, Bare BB (1986) A two-stage decision model for bucking and allocation. Forest Prod J 36(10):70–74
Meredieu C, Colin F, Hervé J-C (1998) Modelling branchiness of Corsican pine with mixed-effect models (*Pinusnigra*Arnold spp. Laricio (Poiret) Maire). Ann Sci Forest 55:359–374
Mitchell KJ (1988) Sylver: modelling the impact of silviculture on yield, lumber value, and economic return. Forest Chron 64:127–131
Mitchell SA (2004) Operational forest harvest scheduling optimisation—a mathematical model and solution strategy. PhD thesis, University of Auckland, New Zealand. pp 278
Moore J (2012) Growing fit-for-purpose structural timber. What is the target and how do we get there? N Z J Forest 57(3):17–24
Moore JR, Lyon AJ, Searles GJ, Vihermaa LE (2009) The effects of site and stand factors on the tree and wood quality of Sitka spruce growing in the United Kingdom. Silva Fenn 43(3):383–396
Moore JR, Lyon AJ, Searles GJ et al (2013) Within– and between-stand variation in selected properties of Sitka spruce sawn timber in the United Kingdom: implications for segregation and grade recovery. Ann Forest Sci (in press)
Münster-Swendsen M (1987) Index of vigour in Norway spruce (*Picea abies* Karst.). J Appl Ecol 24:551–561
Murphy GE (1998) Allocation of stands and cutting patterns to logging crews using a Tabu search heuristic. Int J Forest Eng 9(1):31–38
Murphy G (2003) Reducing trucks on the road through optimal route scheduling and shared log transport services. South J Appl Forest 27:198–205
Murphy G, Lyons J, O'Shea M, Mullooly G, Keane E, Devlin G (2010) Management tools for optimal allocation of wood fibre to conventional log and bio-energy markets in Ireland: a case study. Eur J Forest Res 129:1057–1067. doi:10.1007/s10342-010-0390-3
Newnham RM (1992) Variable-form taper functions for four Alberta species. Can J Forest Res 22:210–223
Ormarsson S, Dahlblom O, Petersson H (1999) A numerical study of the shape stability of sawn timber subjected to moisture variation part 2: simulation of drying board. Wood Sci Technol 33:407–423
Papps SR, Manley BR (1992) Integrating short-term planning with long-term forest estate modelling using FOLPI. In: Proceedings of the conference on integrating forest information over space and time, Canberra, Australia, 13–17 Jan, pp 188–198
Pearson RG (2006) Climate change and the migration capacity of species. Trends Ecol Evol 21(3):111–113
PEFC (2010) Sustainable forest management – requirements: PEFC ST 1003:2010. PEFC, Geneva, p 16, http://www.pefc.org/standards/technical-documentation/pefc-international-standards-2010/676-sustainable-forest-management-pefc-st-10032010
Perera PKP, Amarasekera HS, Weerawardena NDR (2012) Effect of growth rate on wood specific gravity of three alternative timber species in Sri Lanka; *Swietenia macrophylla*, *Khaya senegalensis* and *Paulownia fortune*. J Trop Forest Environ 2(01):26–35
Petersen AK, Solberg B (2005) Environmental and economic impacts of substitution between wood products and alternative materials: a review of micro-level analyses from Norway and Sweden. Forest Policy Econ 7:249–259
Pirotti F, Guarnieri A, Vettore A (2010) Analisi di dati lidar waveform Sulla struttura Della vegetazione e Sulla morfologia costiera. Ital J Remote Sens 42((2):117–127, http://dx.doi.org/10.5721/ItJRS20104229

Pretty JN (1997) The sustainable intensification of agriculture. Nat Resour Forum 21(4):247–256
Putz FE, Sist P, Fredericksen T, Dykstra D (2008) Reduced-impact logging: challenges and opportunities. Forest Ecol Manag 256:1427–1433. doi:10.1016/j.foreco.2008.03.036
Ross RJ, McDonald KA, Green DW, Schad KC (1997) Relationship between log and lumber modulus of elasticity. Forest Prod J 47(2):89–92
Sankaran KV, Chacko KC, Pandalai RC, Mendham DS, Grove TS (2005) Sustaining productivity of eucalypt plantations in Kerala, India. Int For Rev 7(5):14
Schutt C, Aschoff TT, Winterhalder D et al (2004) Approaches for recognition of wood quality of standing trees based on terrestrial laser scanner data. In: ISPRS proceedings of laser-scanners for forest and landscape assessment, Freiburg, Germany 3–6 Oct, pp 179–182
Sedjo RA (1999) The potential of high-yield plantation forestry for meeting timber needs. New Forest 17:339–359
Sedjo RA (2010) The future of trees: climate change and the timber industry. Resources for the future: Winter/Spring 2010, Number 174:29–33. http://www.rff.org/RFF/Documents/Resources_174_2009_Future_of_Trees.pdf
Sepulveda P, Oja J, Gronlund A (2002) Predicting spiral grain by computed tomography of Norway spruce. J Wood Sci 6(48):479–483
Skogforsk (2011) StanForD. Listing of variables by category. http://www.skogforsk.se/PageFiles/60712/AllVarGrp_ENG_110504.pdf. Accessed Oct 13 2011
Suárez J (2010) An analysis of the consequences of stand variability in Sitka spruce plantations in Britain using a combination of airborne LiDAR analysis and models. PhD Thesis, University of Sheffield, p 285
Suárez J, Rosette J, Nicoll B, et al (2008) A practical application of airborne LiDAR for forestry management in Scotland. In: Hill R, Rosette J, Suárez J (eds) 8th international conference on LiDAR applications in forest assessment and inventory, Edinburgh. ISBN 978-0-85538-774-7
Sutton WRJ (1999) The need for planted forests and the example of radiata pine. New Forest 17:95–109
Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable intensification of agriculture. PNAS 108(50):20260–20264, www.pnas.org/cgi/doi/10.1073/pnas.1116437108
Todoroki C, Rönnqvist M (2002) Dynamic control of timber production at a sawmill with log sawing optimization. Scand J Forest Res 17:79–89
Tseheye A, Buchanan AH, Walker JCF (2000) Sorting of logs using acoustics. Wood Sci Technol 34:337–344
Vaisanen H, Kellomaki S, Oker-Blom P, Valtonen E (1989) Structural development of *Pinus silvestris* stands with varying initial density: a preliminary model for quality of sawn timber as affected by silvicultural measures. Scand J Forest Res 4:223–238
van Leeuwen M, Hilkera T, Coops NC, Frazer G, Wulder MA, Newnham GJ, Culvenor DS (2011) Assessment of standing wood and fiber quality using ground and airborne laser scanning: a review. Forest Ecol Manag 261:1467–1478
Vikram V, Cherry ML, Briggs D, Cress DW, Evans R, Howe GT (2011) Stiffness of Douglas-fir lumber: effects of wood properties and genetics. Can J Forest Res 41:1160–1173
Wang JZ, De Groot R (1996) Treatability and durability of heartwood. In: Ritter MA, Duwadi SR, Lee PDH (eds) National conference on wood transportation structures. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, pp 252–260
Wang X, Ross RJ, Carter P (2005) Acoustic evaluation of standing trees – recent research and development. In: Proceedings of the 14th international symposium on nondestructive testing of wood, Eberswalde, Germany, pp 455–465
Wang X, Ross RJ, Carter P (2007a) Acoustic evaluation of wood quality in standing trees part I. Acoustic wave behaviour. Wood Fiber Sci 39(1):28–38
Wang X, Carter P, Ross RJ, Brashaw BK (2007b) Acoustic assessment of wood quality of raw materials – a path to increased profitability. Forest Prod J 57:6–15
Weintraub A, Magendzo A, Magendzo A, Malchuck D, Jones G, Meacham M (1995) Heuristic procedures for solving mixed-integer harvest scheduling-transportation planning models. Can J Forest Res 25:1618–1626

Whiteside ID (1990) STANDPAK modelling system for radiata pine. In: James RN, Tarlton GL (eds) Proceedings of the IUFRO symposium on new approaches to spacing and thinning in plantation forestry. FRI Bull 151. New Zealand Ministry of Forestry, Forest Research Institute, Rotorua, pp 106–111

Whiteside ID, McGregor MJ (1987) Radiata pine sawlog evaluation using the sawing log yield model. In: Kininmonth, JA (ed) Proceedings of the conversion planning conference. FRI Bulletin 128. New Zealand Ministry of Forestry, Forest Research Institute, Rotorua, pp 124–146

Whittenbury CG (1997) Changes in wood products manufacturing. In: Kohn K, Franklin J (eds) Creating a forestry for the 21st century. Island Press, Washington D.C., U.S.A., pp 303–314

Wolcott M (2003) Production methods and platforms for wood plastic composites. In: Proceedings of the non-wood substitutes for solid wood products: new technologies and opportunities for growth conference, Melbourne, Australia

Woollons RC (2000) Comparison of growth of *Pinus radiata* over two rotations in the central north island. Int Forest Rev 2:84–89

Wynne RH (2006) Lidar remote sensing of forest resources at the scale of management. Photogramm Eng Remote Sens 72(12):1310–1314

Yang H-S, Kim DJ, Kim HJ (2003) Rice straw–wood particle composite for sound absorbing wooden construction materials. Bioresour Technol 86:117–121

Zeng H, Pukkala T, Peltola H (2007) The use of heuristic optimization in risk management of wind damage in forest planning. Forest Ecol Manag 241:189–199

Zhu K, Woodall CW, Clark JS (2012) Failure to migrate: lack of tree range expansion in response to climate change. Glob Chang Biol 18(3):1042–1105. doi:10.1111/j.1365-2486.2011.02571.x